NASA TECHNICAL MEMORANDUM

NASA TM X-1935

NASA TM X-1935



# HYDROGEN CAVITATION PERFORMANCE OF 80.6° HELICAL INDUCER MOUNTED IN LINE WITH STATIONARY CENTERBODY

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1970

1. Report No.
NASA TM X-1935

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
HYDROGEN CAVITATION PERFORMANCE OF 80.6° HELICAL INDUCER MOUNTED IN LINE WITH STATIONARY CENTERBODY

5. Report Date
January 1970

6. Performing Organization Code

7. Author(s)
Phillip R. Meng and Royce D. Moore

8. Performing Organization Report No.
E-5243

9. Performing Organization Name and Address
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio 44135

10. Work Unit No.
128-31

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

13. Type of Report and Period Covered
Technical Memorandum

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The performance of an 80.6° helical inducer mounted in an inlet line with a stationary centerbody (inlet annulus) was determined in hydrogen over a temperature range of 31.1° to 41.2° R (17.3 to 22.9 K) and a flow coefficient range of 0.08 to 0.12 at 25 000 and 30 000 rpm. The tank net positive suction head NPSH requirement for the inducer in the annulus configuration was less than that required for the same inducer in a line-mounted configuration, but it was greater than that required for a closely coupled configuration. The inducer NPSH requirement increased with increasing flow coefficient and rotative speed and decreased with increasing hydrogen temperature.

17. Key Words (Suggested by Author(s))
Hydrogen inducers
Two-phase flow
Cavitation

18. Distribution Statement
Unclassified - unlimited

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price* |
|---|---|---|---|
| Unclassified | Unclassified | 19 | $3.00 |

*For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151

# HYDROGEN CAVITATION PERFORMANCE OF 80.6° HELICAL INDUCER MOUNTED IN LINE WITH STATIONARY CENTERBODY

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## SUMMARY

The noncavitating and cavitating performance of an 80.6° helical inducer was determined in liquid hydrogen. The inducer was installed in an inlet line with a stationary centerbody (inlet annulus), which extended 26.5 inches (67.3 cm) upstream of the blade leading edges. The net positive suction head NPSH requirements for the inducer were determined over a liquid-hydrogen temperature range of 31.1° to 41.2° R (17.3 to 22.9 K) and a flow coefficient range of 0.08 to 0.12 at rotative speeds of 25 000 and 30 000 rpm. The tank NPSH requirement for the inducer in the annulus configuration was compared with the requirement for the same inducer in a line-mounted configuration and also with the inducer in a short inlet, which simulated a closely coupled configuration. The tank NPSH requirement was less for the inducer in the annulus configuration than that for the line-mounted configuration but was greater than that for the closely coupled configuration. The variation in tank NPSH requirements is attributed to the different head losses that occur in each of the three inlet configurations. For a constant rotative speed, the required NPSH for the inducer operated at a given performance level decreased with increasing liquid temperature and increased with increasing flow coefficient. With vapor present at the inducer inlet, the required inducer NPSH was greater for the inlet annulus than that for the inlet line configuration. The noncavitating performance of the inducer was unaffected by liquid temperature, rotative speed, and inlet line configuration.

## INTRODUCTION

In hydrogen-fueled rocket vehicles, large-volume tanks are required to contain the low-density liquid hydrogen. The weight of these fuel tanks and, thus the payload capability, is sensitive to the tank pressure. It is, therefore, desirable to design the tanks for the lowest pressure that will satisfy the inlet pressure requirements of the turbopump. The cavitating inducer is used upstream of the main pump to reduce the pressure requirements. The turbopump is usually installed in a line downstream from the fuel tank. Thus, line entrance pressure losses and pressure losses encountered in the line from the tank to the pump must be considered. These pressure losses will increase the tank pressure requirements.

In a previous investigation (ref. 1), the net positive suction head (NPSH) requirements of an $80.6^{\circ}$ helical inducer were determined over a range of liquid temperatures and flows. The inducer was tested with a very short inlet line to simulate an inducer closely coupled to the fuel tank. With such an inlet configuration, the pressure losses from the tank to the inducer were considered negligible. In another investigation (ref. 2), the NPSH requirements of the same $80.6^{\circ}$ helical inducer were determined over a similar range of flow conditions with a 26.5-inch- (67.3-cm-) long inlet line. A comparison of the two inlet line configurations showed that the tank NPSH requirement was greater with the longer inlet line. The increase in NPSH requirements is attributed to the losses associated with the longer inlet line. In the present investigation, a stationary centerbody was installed in the 26.5-inch- (67.3-cm-) long inlet line of reference 2, and the same $80.6^{\circ}$ helical inducer was tested in this inlet annulus configuration.

The objective of this investigation was to determine the NPSH requirements for the $80.6^{\circ}$ helical inducer installed in the inlet annulus and to compare the tank pressure requirements for this type of configuration with those for the closely coupled and the 26.5-inch (67.3-cm) inlet line configurations. The experimental inducer was tested over a liquid temperature range of $31.1^{\circ}$ to $41.2^{\circ}$ R (17.3 to 22.9 K). The flow coefficient was varied from 0.08 to 0.12 at rotative speeds of 25 000 and 30 000 rpm. These tests were conducted at the NASA Lewis Research Center Plum Brook Station.

## SYMBOLS

| | |
|---|---|
| $C_d$ | head-loss coefficient |
| g | acceleration due to gravity, 32.2 ft/sec$^2$ (9.8 m/sec$^2$) |
| $\Delta H$ | inducer head rise, ft of liquid; m of liquid |
| NPSH | net positive suction head, ft of liquid; m of liquid |
| $U_t$ | blade tip speed, ft/sec; m/sec |
| $V_a$ | average axial velocity immediately upstream of inducer inlet, ft/sec; m/sec |
| $\phi$ | flow coefficient, $V_a/U_t$ |
| $\psi$ | head-rise coefficient, $g\ \Delta H/U_t^2$ |

Subscripts:

NC noncavitating

T tank

# APPARATUS AND PROCEDURE

## Test Inducer

The test rotor used in this investigation was a three-bladed, flat-plate helical inducer with a tip helix angle of 80.6°. The inducer had a tip diameter of 4.980 inches (12.65 cm) and a hub- to tip-diameter ratio of 0.5. Both the tip diameter and the diameter ratio were maintained constant across the rotor. Significant geometric features, as well as a photograph of the inducer, are shown in figure 1. The leading edges of the inducer blades were faired on the suction surface only (see fig. 1).

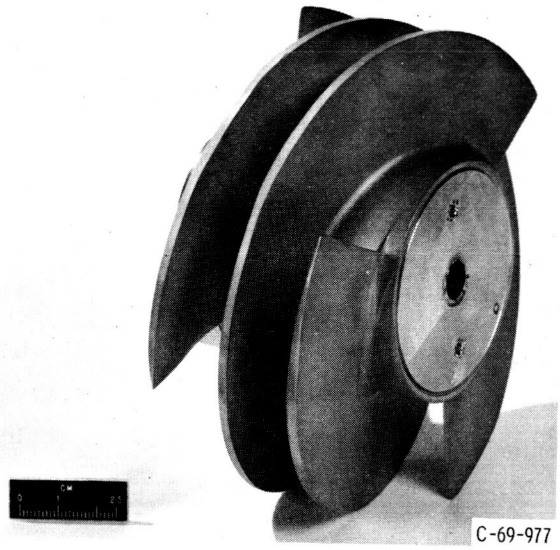
## Test Facility

This investigation was conducted in the liquid-hydrogen pump test facility shown schematically in figure 2. The inducer was installed in an inlet annulus that extended 26.5 inches (67.3 cm) above the blade leading edges. The inducer was located near the bottom of the 2500-gallon (9.5-$m^3$) vacuum-jacketed research tank. A booster rotor located downstream of the inducer was used to overcome system losses. The flow path is down the inlet annulus, through the inducer and booster rotor to a collector scroll, and into a discharge line to the storage dewar. For test runs above 36.5° R (18.3 K), the liquid was recirculated through the research tank to extend run time.

The facility is basically the same as that described in references 1 to 4. For the tests reported herein, a stationary centerbody was installed in the inlet line configuration that was used for the tests reported in reference 2. The stationary centerbody extends from the entrance to the inlet line to the inducer hub and is held in place by four vanes at the entrance and by three centering rods at the inducer end. The annulus formed by the inlet line and the centerbody has the same cross-sectional area as the inducer inlet area.

## Test Procedure

The research tank was filled with liquid hydrogen from the storage dewar. Prior to each test, the hydrogen in the tank was conditioned to the desired liquid temperature




| | |
|---|---|
| Tip helix angle (from axial direction), deg | 80.6 |
| Rotor tip diameter, in. (cm) | 4.980 (12.649) |
| Rotor hub diameter, in. (cm) | 2.478 (6.294) |
| Hub-tip ratio | 0.496 |
| Number of blades | 3 |
| Axial length, in. (cm) | 2.00 (5.08) |
| Peripheral extent of blades, deg | 280 |
| Tip chord length, in. (cm) | 12.35 (31.37) |
| Hub chord length, in. (cm) | 6.36 (16.15) |
| Solidity at tip | 2.350 |
| Tip blade thickness, in. (cm) | 0.100 (0.254) |
| Hub blade thickness, in. (cm) | 0.150 (0.381) |
| Calculated radial tip clearance at hydrogen temperature, in. (cm) | 0.025 (0.064) |
| Ratio of tip clearance to blade height | 0.020 |
| Material | 6061-T6 Aluminum |

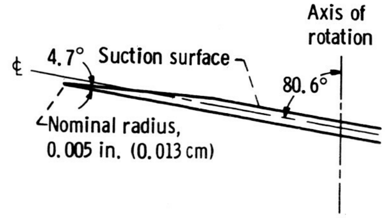



Figure 1. - Geometric details of 80.6° helical inducer.

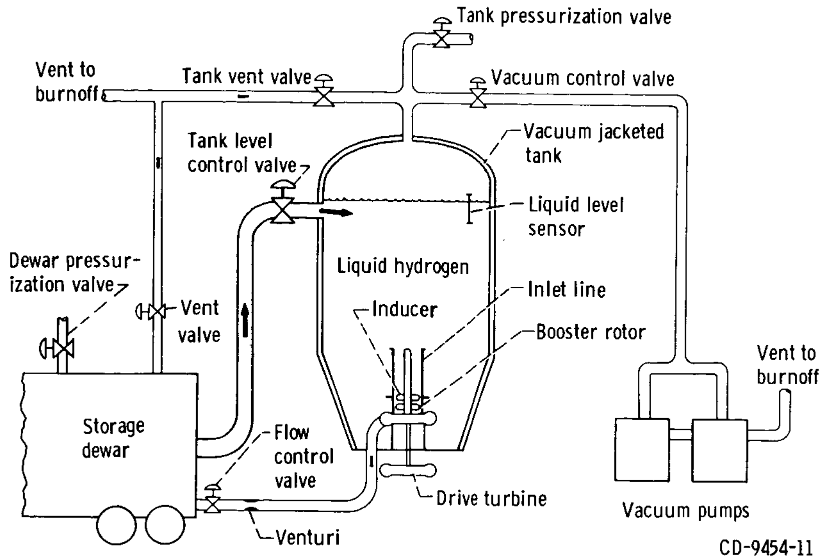
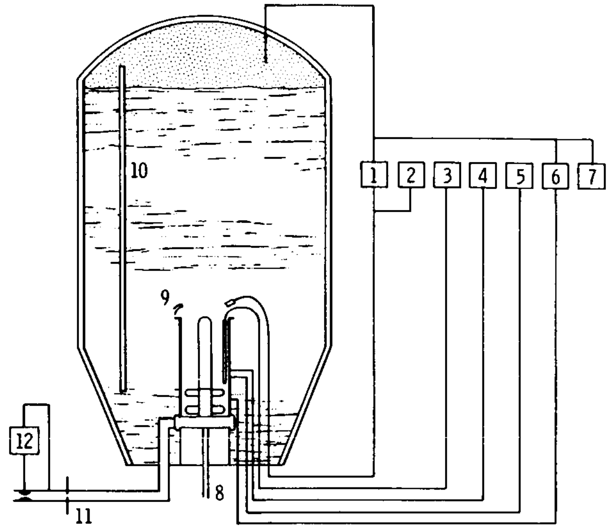



Figure 2. - Liquid-hydrogen pump test facility.

either by subjecting the liquid to a vacuum for the colder runs or by recirculating the liquid for the warmer runs. For the cavitating runs, the tank was pressurized to 10 psi (6.9 $N/cm^2$) above the liquid vapor pressure. When the desired rotative speed was attained, the tank pressure (NPSH) was slowly reduced until the head rise deteriorated because of cavitation. The flow rate and bulk liquid temperature were maintained essentially constant during each test. The noncavitating performance was obtained by varying the flow rate while maintaining a constant rotative speed and liquid temperature. The tank pressure for the noncavitating runs was maintained at 15 psi (10.4 $N/cm^2$) above the liquid vapor pressure.

The location of the instrumentation used in this investigation is shown schematically in figure 3. The measured parameters and the estimated maximum system errors are also listed in figure 3.

The liquid vapor pressure was measured with a vapor pressure bulb that was charged with hydrogen from the tank. One vapor pressure bulb was located at the entrance to the inlet line. Another vapor pressure bulb was utilized to measure vapor pressure at the inducer inlet. Tank pressure, measured in the ullage space, was used as the reference pressure for the differential pressure transducers. The liquid level above the inducer, measured by a capacitance gage, was added to the reference pressure to correct the differential pressures to the inducer inlet conditions. An averaged hydrogen temperature at the inducer inlet was obtained from two platinum resistor thermometers. A shielded total pressure probe, located at midstream approximately 1 inch (2.54 cm) downstream of the test rotor, was used to measure the inducer pressure rise. Pump flow rate was obtained with a Venturi flowmeter that was calibrated in water.




| Item number | Parameter | Estimated system accuracy | Number of instruments used | Remarks |
|---|---|---|---|---|
| 1 | Tank net positive suction head, psi ($N/cm^2$) | Low range ±0.05 (±0.035) | 1 | Measured as differential pressure (converted to head of liquid) between vapor bulb at line inlet and tank pressure corrected to line inlet conditions |
| | | High range ±0.25 (±0.17) | | |
| 2 | Vapor pressure at line inlet, psi ($N/cm^2$) | ±0.25 (±0.17) | 1 | Vapor bulb charged with liquid hydrogen from research tank |
| 3 | Vapor pressure at inducer inlet, psi ($N/cm^2$) | ±0.25 (±0.17) | 1 | Long, small-diameter vapor bulb with streamlined trailing edge alined with flow stream to minimize bulb cavitation |
| 4 | Static pressure (line), psi ($N/cm^2$) | ±0.05 (±0.035) | 1 | Average of three pressure taps (120° apart) located 10.5 in. (26.6 cm) above inducer inlet |
| 5 | Total pressure (line), psi ($N/cm^2$) | ±0.05 (±0.035) | 1 | Shielded total pressure probe located 0.065 in. (0.165 cm) in from wall and 10.5 in. (26.6 cm) upstream of inducer |
| 6 | Inducer pressure rise, psi ($N/cm^2$) | ±1.0 (±0.69) | 1 | Shielded total pressure probe at mid-passage 1 in. (2.54 cm) downstream of inducer |
| 7 | Tank pressure, psi ($N/cm^2$) | ±0.5 (±0.35) | 1 | Measured in tank ullage and corrected to inducer inlet conditions for reference pressure for differential transducers |
| 8 | Rotative speed, rpm | ±150 | 1 | Magnetic pickup in conjunction with gear on turbine drive shaft |
| 9 | Line inlet temperature, °R (K) | ±0.1 (±0.06) | 2 | Platinum resistor probes 180° apart at inlet |
| 10 | Liquid level, ft (m) | ±0.5 (±0.15) | 1 | Capacitance gage, used for hydrostatic head correction to inducer inlet conditions |
| 11 | Venturi inlet temperature, °R (K) | ±0.1 (±0.06) | 1 | Platinum resistor probe upstream of Venturi |
| 12 | Venturi differential pressure, psi ($N/cm^2$) | ±0.25 (±0.17) | 1 | Venturi calibrated in air |

Figure 3. - Instrumentation for liquid-hydrogen pump test facility.

The differential pressure measured directly between the tank pressure and the vapor bulb at the annulus inlet was corrected to feet (m) of head to obtain tank NPSH. Inducer NPSH was obtained by subtracting the annulus losses from the tank NPSH. The losses were calculated by multiplying the annulus fluid velocity head by the loss coefficient, which was determined to be 0.20 from calibrations in air.

# RESULTS AND DISCUSSION

## Noncavitating Performance

The noncavitating performance of the 80.6° helical inducer is shown in figure 4, where head-rise coefficient $\psi_{NC}$ is plotted as a function of flow coefficient $\phi$. Several

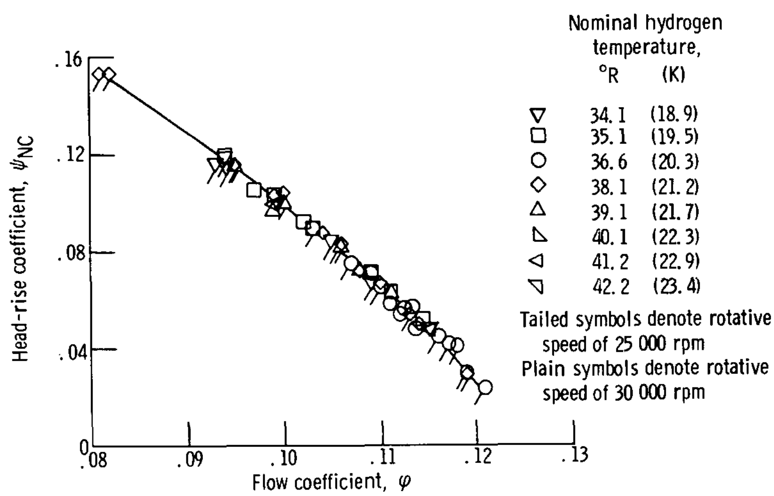
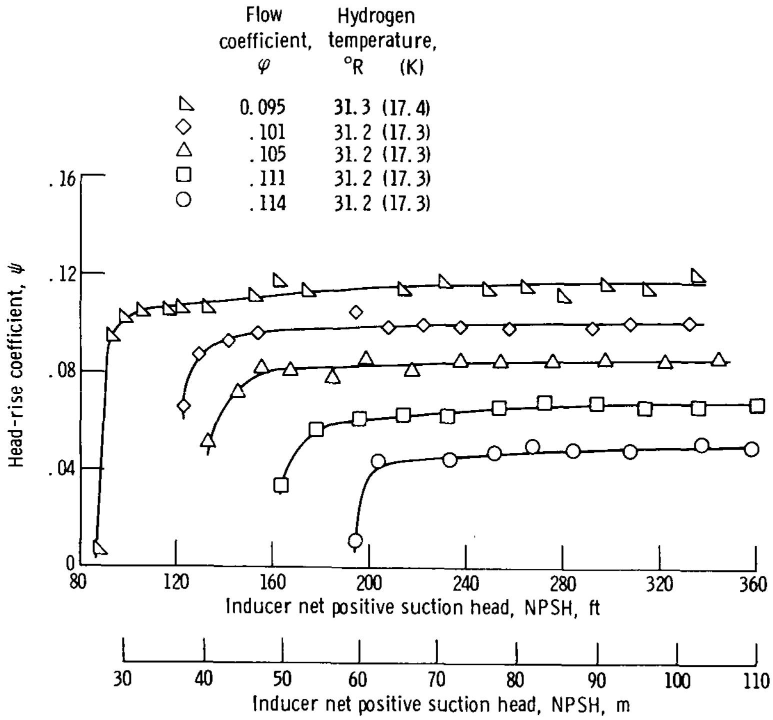



Figure 4. - Noncavitating performance of 80.6° helical inducer in hydrogen.

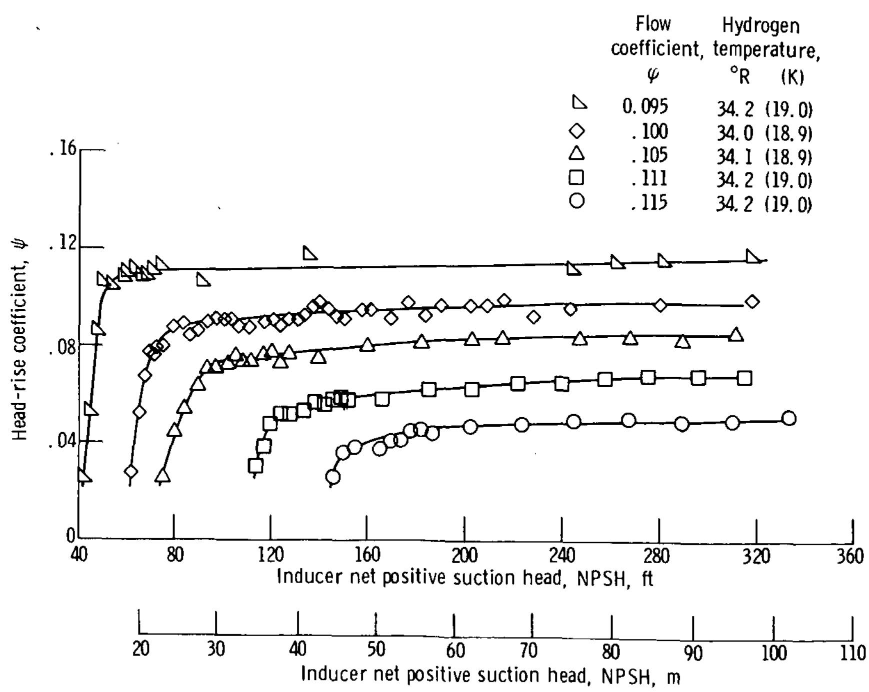
nominal hydrogen temperatures are shown for test rotative speeds of 25 000 and 30 000 rpm. As expected, neither liquid temperature nor rotative speed has any measurable effect on the head-rise coefficient. As in the previous investigations of this inducer, the head-rise coefficient decreased almost linearly with increasing flow coefficient. A comparison of the data of figure 4 with that of references 1 and 2 indicated that there was no measurable difference in the noncavitating performance among the three types of inlet configurations.

## Cavitation Performance

The inducer cavitation performance for the two rotative speeds is shown in figures 5

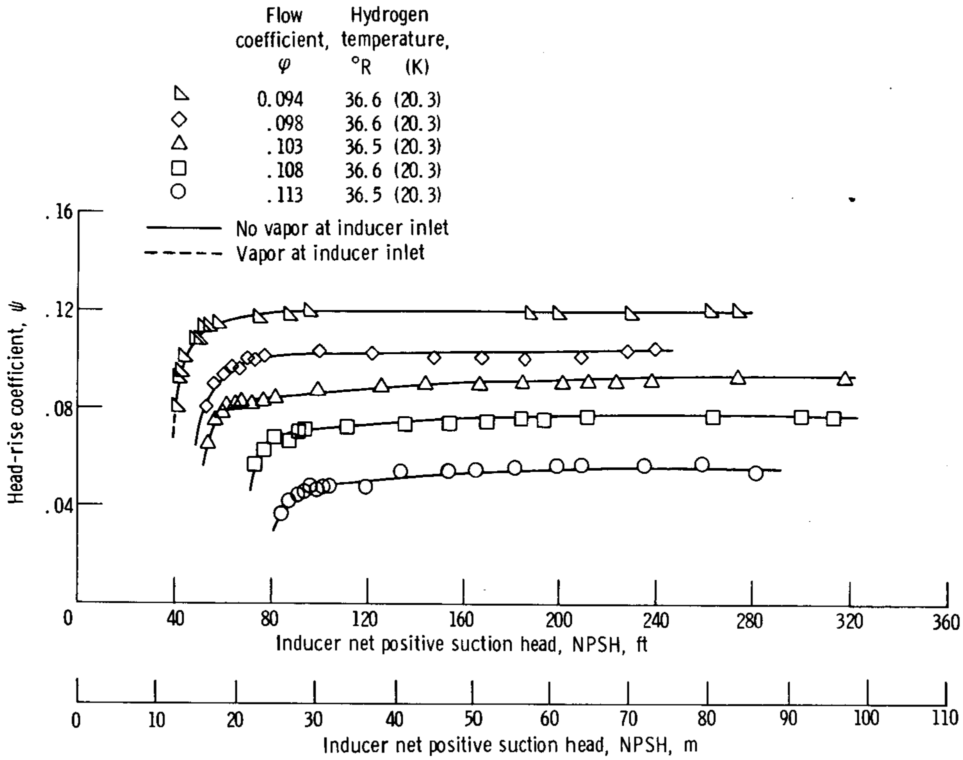



(a) Nominal hydrogen temperature, 31.2° R (17.3 K).

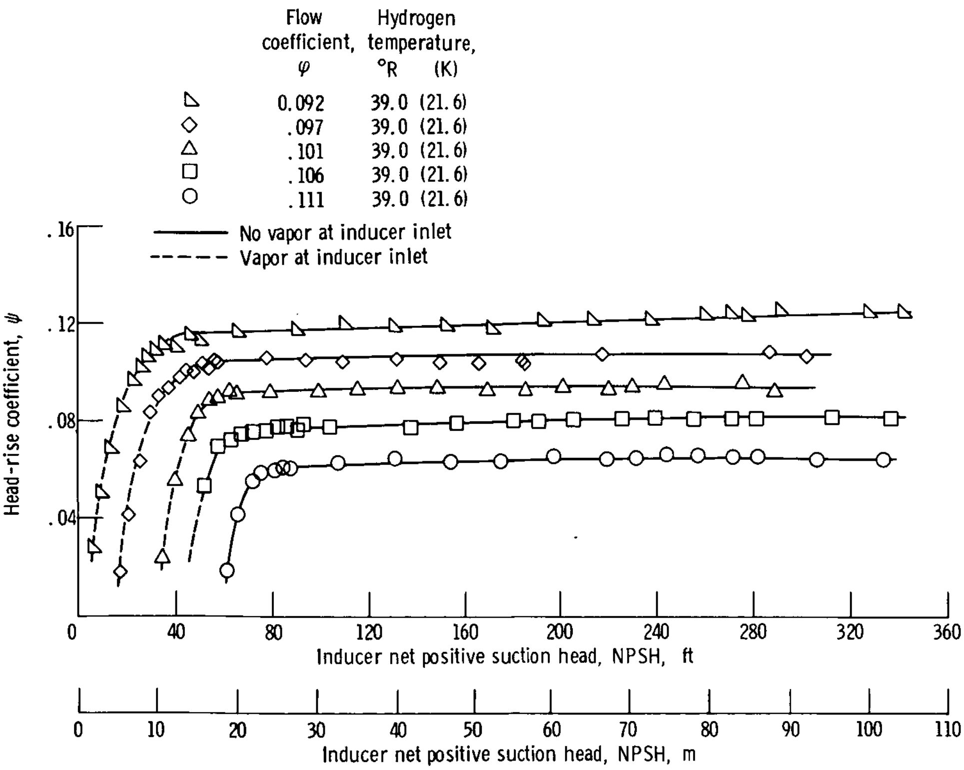



(b) Nominal hydrogen temperature, 34.1° R (18.9 K).

Figure 5. - Cavitation performance of 80.6° helical inducer in hydrogen at 25 000 rpm.

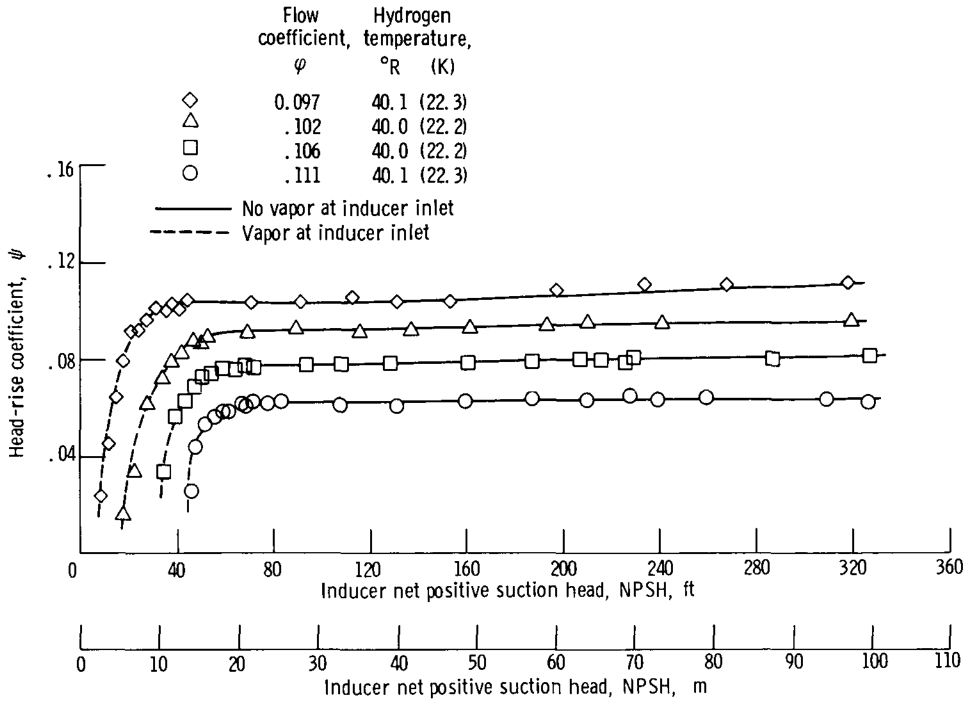



(c) Nominal hydrogen temperature, 36.6° R (20.3 K).




(d) Nominal hydrogen temperature, 39.0° R (21.6 K).

Figure 5. - Continued.




(e) Nominal hydrogen temperature, 40.0° R (22.2 K).

Figure 5. - Concluded.

and 6, where head-rise coefficient is plotted as a function of NPSH. The data at each nominal hydrogen temperature are shown for several values of flow coefficient in figure 5 for a rotative speed of 25 000 rpm. Similar data are presented in figure 6 for a rotative speed of 30 000 rpm. At the highest liquid temperatures (figs. 5(e) and 6(e) and (f)), data were not obtained over the complete range of flow coefficient. The cavitation performance with no vapor at the inducer inlet is shown by the solid portion of the curves, whereas the cavitation performance with vapor in the inlet is shown by the dashed portion on some of the curves. Vapor was assumed to be present at the inducer inlet when the NPSH was equal to or less than the calculated inlet fluid velocity head.

At a rotative speed of 25 000 rpm (figs. 5(d) and (e)), the head-rise coefficient begins to fall off in most cases before the inducer NPSH is lowered to the value of the inlet velocity head, that is, before vapor is formed in the inlet line. In contrast, the same inducer in the inlet line configuration of reference 2 did not experience a fall off in head rise coefficient at the same operating conditions until the inducer NPSH was reduced to at least 20 feet (6.1 m) below the inlet velocity head. These data indicate a notable difference in inducer cavitation performance between the two inlet configurations when vapor is present at the inducer inlet.

The results of reference 4 indicate that, when two-phase flow is present in the inlet

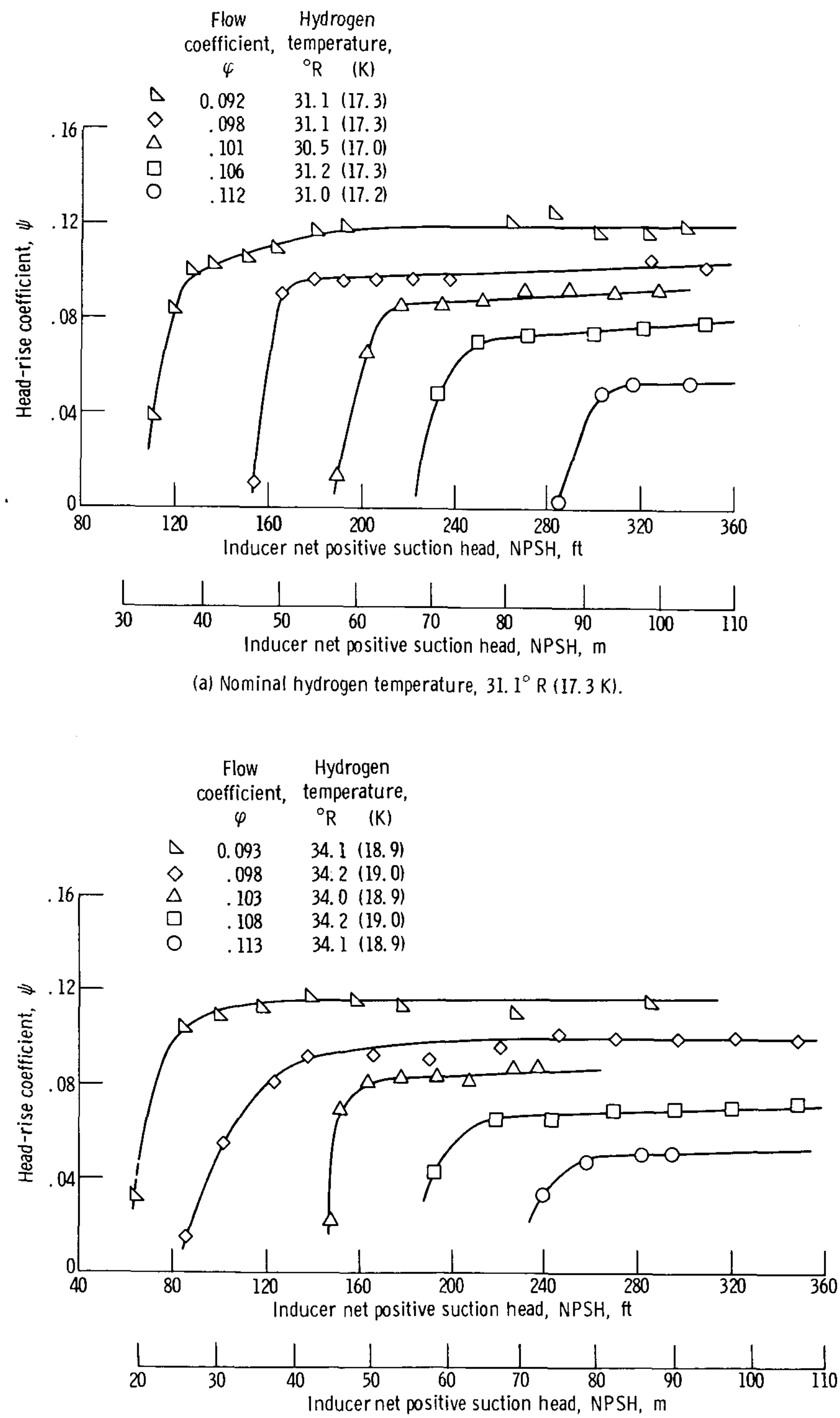
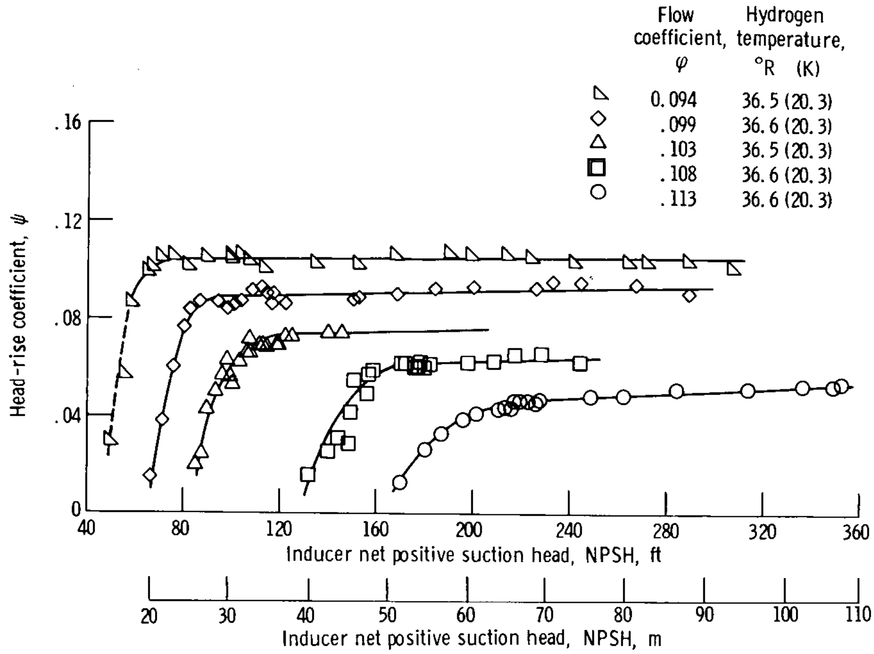
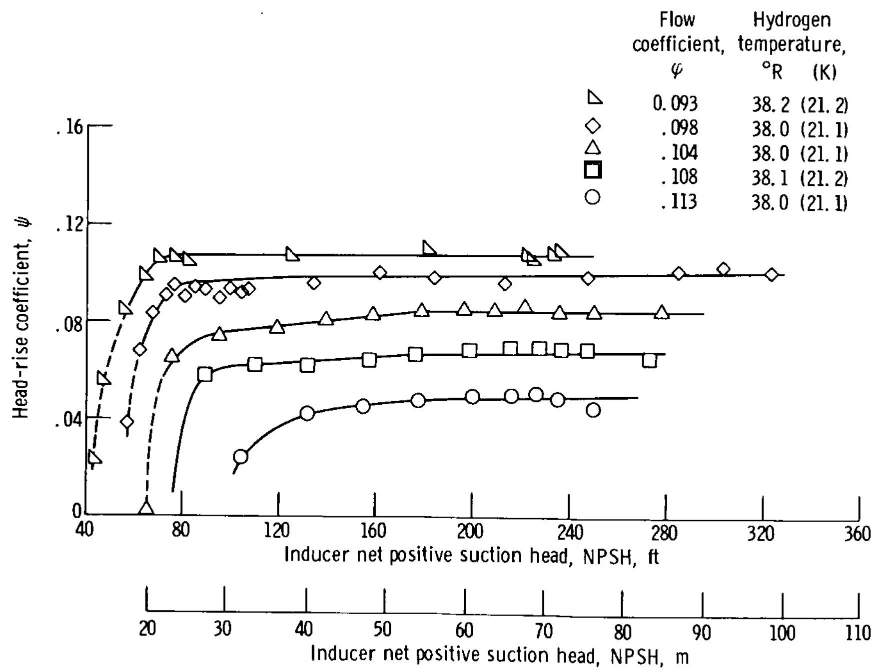



Figure 6. - Cavitation performance of 80.6° helical inducer in hydrogen at 30 000 rpm.

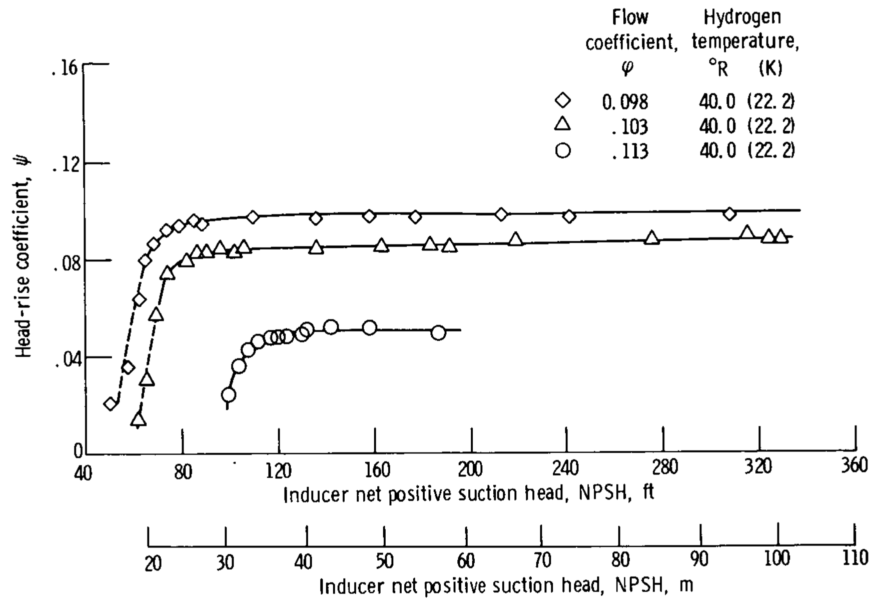



(c) Nominal hydrogen temperature, 36.6° R (20.3 K).

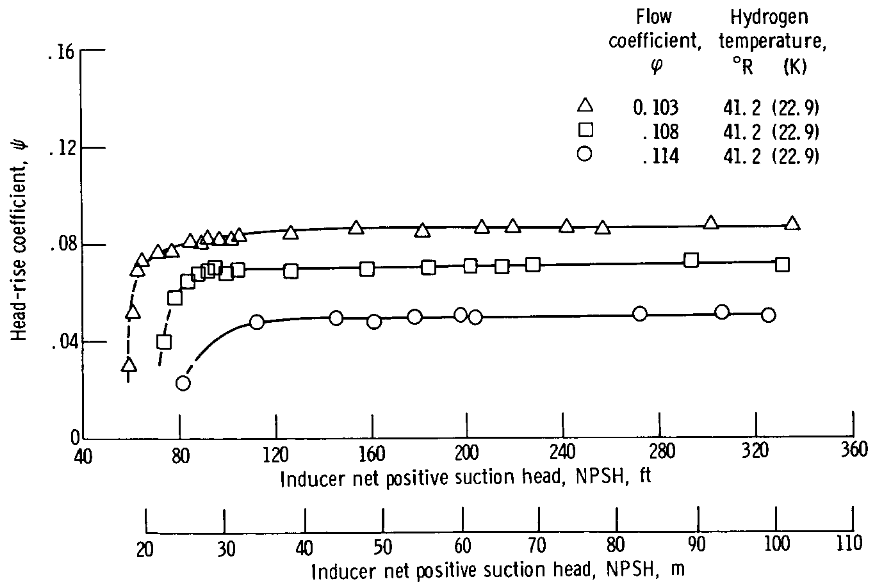



(d) Nominal hydrogen temperature, 38.1° R (21.2 K).

Figure 6. - Continued.




(e) Nominal hydrogen temperature, 40.0° R (22.2 K).




(f) Nominal hydrogen temperature, 41.2° R (22.9 K).

Figure 6. - Concluded.

line, the inducer performs as though it were operating at a higher value of flow coefficient to account for the higher volume flow rate at the inducer inlet. The volume of vapor formed is dependent on the properties of the liquid and its vapor and on the local fluid velocity. A higher fluid velocity occurs upstream of the inducer, and thus more vapor is formed in the inlet annulus than in the inlet line configuration. Therefore, the inducer in the inlet annulus configuration operates at a higher effective flow coefficient than the same inducer would in the inlet line configuration. Since the NPSH requirement of this inducer increases with increasing flow coefficient, the higher NPSH requirement with vapor present was expected with the inlet annulus configuration.

As in the previous reports on this inducer (refs. 1 and 2), several general trends can be observed from the curves of figures 5 and 6. For a given rotative speed and flow coefficient, the required NPSH for a given performance level decreased with increasing liquid temperature. At a given temperature and rotative speed, the required NPSH decreased with decreasing flow coefficient for a given performance level. The required NPSH increased substantially with the increase in rotative speed from 25 000 to 30 000 rpm for a given flow coefficient and liquid temperature.

These trends are summarized in figures 7 and 8, where the required NPSH for a head-rise-coefficient ratio $\psi/\psi_{NC}$ of 0.70 is plotted as a function of flow coefficient $\phi$. The required NPSH is plotted for several nominal hydrogen temperatures at rotative speeds of 25 000 and 30 000 rpm (figs. 7 and 8, respectively). Values of NPSH less than the calculated velocity head $V_a^2/2g$ are indicated by the shaded area in these figures. When the NPSH is lowered to the inlet fluid velocity head, the inlet static pressure is equal to the inlet fluid vapor pressure. A further reduction in NPSH will cause the inlet fluid to boil and vapor to be ingested by the inducer. This condition of vapor at the inducer inlet is indicated by the dashed portion of some of the curves of figures 7 and 8. The solid portion of these curves represents the performance with no vapor present at the inducer inlet. The performance with no vapor at the inducer inlet (solid lines) shows that the required NPSH increased rapidly with increasing flow coefficient and that the required NPSH decreased significantly with increasing liquid temperature. Both these trends are evident at the two rotative speeds, but the magnitude of the required NPSH is much greater at the higher rotative speed.

At a rotative speed of 25 000 rpm (fig. 7) with vapor in the inducer inlet (dashed lines), the required NPSH continued to decrease to values below the inlet fluid velocity head at liquid temperatures greater than $36.6^{\circ}$ R (20.3 K). The dashed portion of the curve representing the performance at a liquid temperature of $36.6^{\circ}$ R (20.3 K) appears to remain at the fluid velocity head. At 30 000 rpm with vapor at the inducer inlet (fig. 8), the required NPSH remained essentially equal to the inlet fluid velocity head for liquid temperatures of $36.6^{\circ}$ to $41.2^{\circ}$ R (20.3 to 22.9 K).

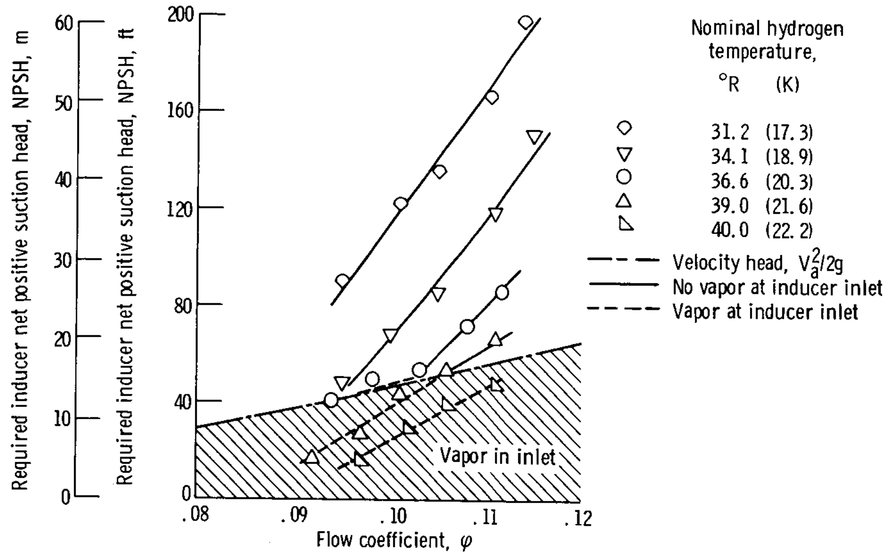



Figure 7. - Variation of inducer cavitation performance with flow coefficient at several hydrogen temperatures. Rotative speed, 25 000 rpm; head-rise-coefficient ratio, 0.70.

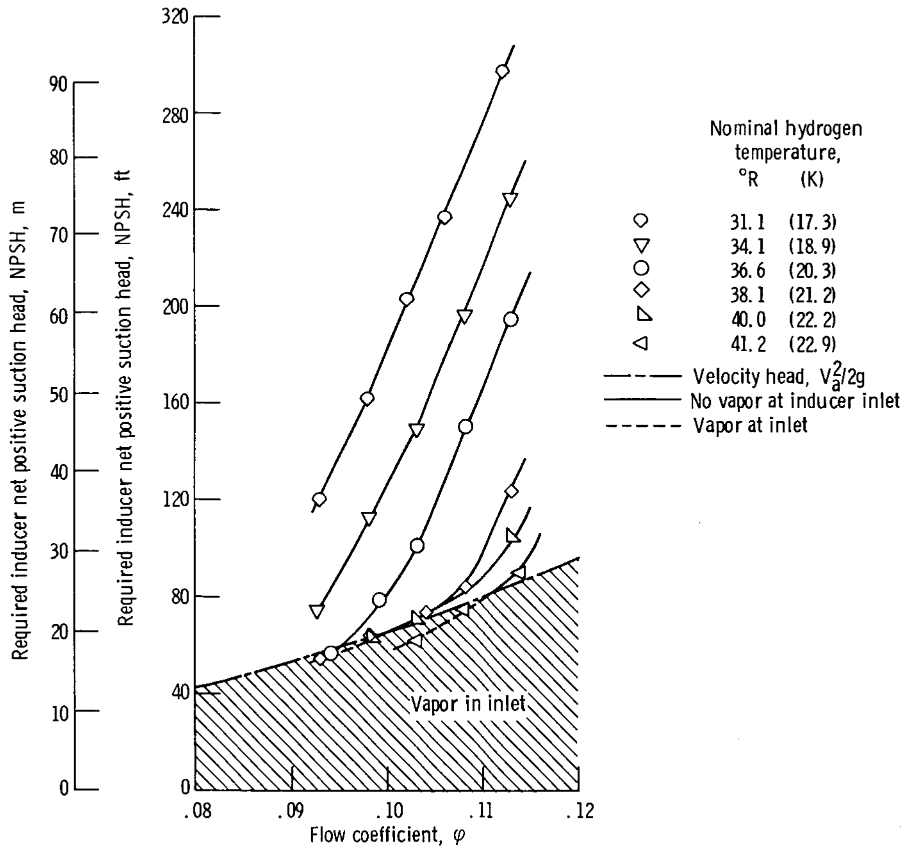



Figure 8. - Variation of inducer cavitation performance with flow coefficient at several hydrogen temperatures. Rotative speed, 30 000 rpm; head-rise-coefficient ratio, 0.70.

## Tank Net Positive Suction Head

A comparison of the tank NPSH required for a 0.70-head-rise-coefficient ratio at various flow coefficients is shown for each of the three inlet line configurations in figure 9. The data shown are for a liquid-hydrogen temperature of $38.2^{\circ}$ R (21.2 K). Although the required tank NPSH for the inlet annulus was less than that required for the inlet line configuration (ref. 2), they were both greater than that required for the closely coupled inducer (ref. 1). The variation in required tank NPSH is attributed to the differences in head-loss coefficient $C_d$ for the three configurations. The head-loss coefficient, as determined by calibration in air, for the inlet annulus was 0.20 as compared with 0.75 for the inlet line configuration. For the closely coupled inducer, the head-loss coefficient was considered to be negligible. The dashed portion of each of the three curves indicates the inducer performance with vapor at the inlet. The start of the vaporous region does not occur at the same flow coefficient for each inlet configuration because of the differences in the head losses. In general, the tank NPSH requirements at the other hydrogen temperatures had similar trends to those shown in figure 9 for a temperature of $38.2^{\circ}$ R (21.2 K) at a head-coefficient ratio of 0.70.

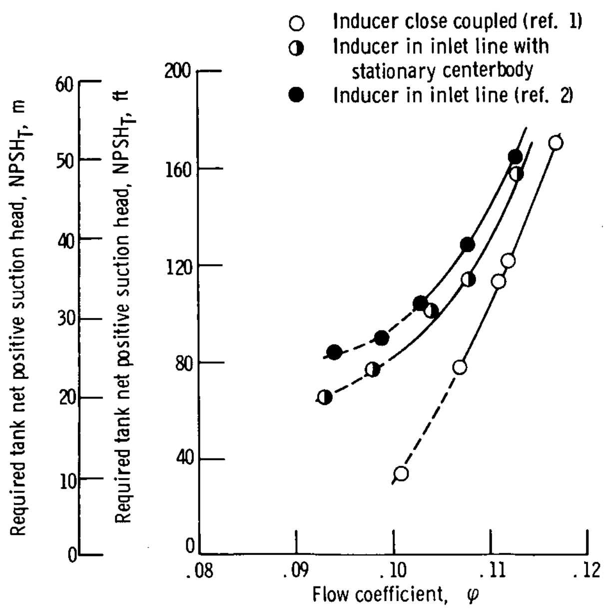



Figure 9. - Comparison of tank net positive suction head requirement for $80.6^{\circ}$ helical inducer with three different inlet configurations. Rotative speed, 30 000 rpm; hydrogen temperature, $38.2^{\circ}$ R (21.2 K); inducer head-rise-coefficient ratio, 0.70.

# SUMMARY OF RESULTS

The noncavitating and cavitating performance of an 80.6° helical inducer was evaluated in liquid hydrogen. The net positive suction head NPSH requirements were determined over a liquid temperature range of 31.1° to 41.2° R (17.3 to 22.9 K) and a flow coefficient range of 0.08 to 0.12 at rotative speeds of 25 000 and 30 000 rpm. The experimental inducer was installed in an inlet annulus (inlet line with stationary centerbody) which extended 26.5 inches (67.3 cm) above the blade leading edges. The tank pressure requirements for this inlet annulus configuration were compared with those for the same inducer in an inlet line configuration and for a closely coupled inducer. The following results were obtained:

1. The tank NPSH requirement for a head-rise-coefficient ratio of 0.7 for the inlet annulus configuration was slightly less than that for the inlet line configuration, but it is greater than that required for the closely coupled inducer. The variations in the NPSH requirements were attributed to the difference in the head losses between each of the inlet configurations.

2. At a given performance level, the required inducer NPSH increased with increasing flow coefficient and decreased with increasing liquid temperature. The required NPSH was increased as the inducer rotative speed was increased from 25 000 to 30 000 rpm.

3. With vapor present at the inducer inlet, a higher value of inducer NPSH was required for the inlet annulus than that required for the inlet line configuration.

4. The noncavitating head-rise coefficient, which decreased almost linearly with increasing flow coefficient, was unaffected by liquid temperature, rotative speed, and inlet configuration.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 15, 1969,
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